

**EXHIBIT C**

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## Calcium Phosphates in Oral Biology and Medicine

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## About the Author

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## 2.3. Preparation of Biologically Relevant Calcium Phosphates

To characterize the biological Ca-P, it has been necessary to use pure synthetic Ca-P compounds as standards. The methods of preparation briefly described below are recommended based on their simplicity and reproducibility.

The appropriate physical methods which should be used to confirm the identity of the products are XRD, IR absorption spectroscopy, elemental analyses of calcium and phosphate concentrations. (For substituted whitlockites or apatites, the concentration of the substituting ion, e.g., fluoride, carbonate, magnesium, strontium, should of course be determined.) Calcium and phosphate analyses alone (expressed as Ca/P weight or molar ratio) are not acceptable since the Ca/P ratio does not distinguish between pure and mixed Ca-P phases. For example, a Ca/P molar ratio of 1.33 may be pure OCP, or a mixture of DCPD and TCP or a mixture of DCPD and AP. Indirect identification of the Ca-P phase by analyses of the Ca/P molar ratio of the solution is misleading since the Ca/P values of solutions will not distinguish pure from mixed Ca-P phases in the solids. Since each compound has its own crystal structure, XRD is one of the most conclusive means of identification of a Ca-P phase. A combination of XRD, IR and elemental analyses will give the best characterization of a Ca-P preparation.

## 1. Amorphous Calcium Phosphate

ACP containing only calcium and phosphate ions may be prepared at room temperature by the rapid addition of basic  $\text{Ca}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$  solution (11.75 g  $\text{Ca}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$  reagent dissolved in 137 ml distilled  $\text{H}_2\text{O}$ +10 ml conc.  $\text{NH}_4\text{OH}$ ) to a stirring basic phosphate solution (6.5 g  $(\text{NH}_4)_2\text{HPO}_4$  dissolved in 325 ml  $\text{H}_2\text{O}$ +10 ml  $\text{NH}_4\text{OH}$ , filtered, washed and dried. The ACP formed in this manner was calculated to have the formula:  $\text{Ca}_3(\text{PO}_4)_{1.8}(\text{HPO}_4)_{0.2} \cdot x\text{H}_2\text{O}$  [184]. The use of highly concentrated solutions are common features for the described methods of preparing ACP [51, 127, 184, 245, 289, 396]. Unsubstituted ACP (i.e., prepared in the presence of phosphate ions) and substituted ACP (i.e., prepared in the presence of carbonate, magnesium or pyrophosphate) give XRD patterns identical to figure 2.4a [219, 245]. Unsubstituted ACP which gives an IR absorption spectrum shown in figure 2.4b has a Ca/P ratio of about 1.5 and a typical morphology of hollow spheres (fig. 2.4c). It should be noted that unsubstituted ACP is unstable in solution [184, 245, 396] and even when stored dry,

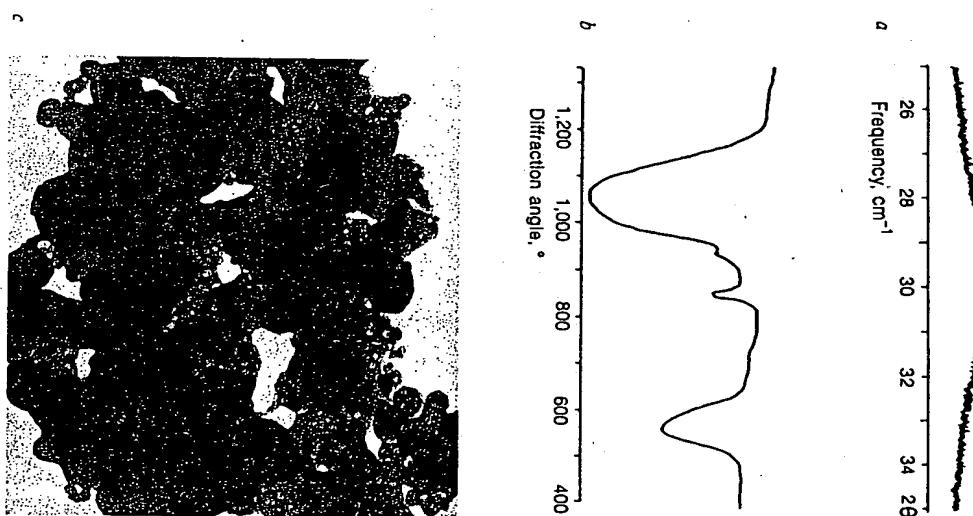


Fig. 2.4. a XRD pattern of amorphous calcium phosphate, ACP, with the characteristic absence of diffraction peaks and broad maxima between 28 and 32° $2\theta$  [219, 245]. b IR spectrum of ACP containing only calcium and inorganic phosphate is characterized by lack of resolution of the  $\text{PO}_4$  absorption bands [219, 245, 283]. c TEM of ACP with XRD pattern and IR spectrum shown in figures 2.4a and b, respectively. The characteristic feature of the TEM of ACP is the presence of hollow spheres [127, 245].

## 7. Calcium Hydroxyapatites

Apatites which have been used as prototypes of biological apatites, especially of enamel apatites, have been prepared by the following methods: (a) precipitation and subsequent sintering [180, 197, 273]; (b) precipitation at 70 or 100 °C with long periods of digestion [142, 219, 222, 236, 240, 251, 298, 406]; (c) hydrothermal methods [209, 219, 386]; and (d) solid-state diffusion methods [218, 386]. Such apatites have been used to serve as analogues of enamel in determining the dissolution characteristics, adsorptive properties and mechanism of substitution of some elements.

a. *Pure Ca-OH-Ap,  $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$* . Pure HA, like pure  $\beta$ -TCP, is not obtained from aqueous systems. HA is obtained by solid-state reactions hydrothermally at 375 °C, or at temperatures above 900 °C [207, 219, 273, 386]. HA is also obtained when apatites precipitated from very basic solutions ( $\text{pH} > 11$ ) are sintered above 900 °C [180, 197]. A method originally developed by Hayek and Newesely [180] and modified by others [197] consisted of titrating with  $\text{H}_3\text{PO}_4$ , a saturated solution of  $\text{Ca}(\text{OH})_2$  (whose pH was adjusted to 12 with concentrated  $\text{NH}_4\text{OH}$ ), sintering the precipitate at

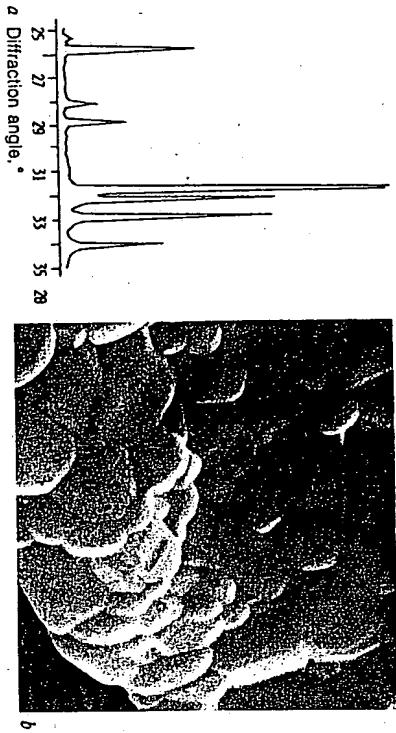


Fig. 2.10. a XRD pattern of calcium hydroxyapatite, HA,  $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ , prepared by precipitation and subsequent sintering at 950 °C. Unit cell dimensions:  $a = 0.921 \text{ nm}$ ;  $c = 0.6880 \text{ nm}$ . b SEM of HA prepared by precipitation and subsequent sintering at 950 °C.

900 °C. A solid-state method (TVA method) is by the reaction of  $\text{CaCO}_3$  and  $\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$  with  $\text{Ca}/\text{P}$  ratio of 1.67 at 1,200 °C [273]. Pure HA gives XRD pattern of figure 2.10a with lattice parameters:  $a = 9.421$  and  $c = 6.880 \pm 0.003 \text{ \AA}$ ; morphology shown in figure 2.10b,  $\text{Ca}/\text{P}$  ratio = 1.67 (table 2.1).

*Biological occurrence:* Stoichiometric apatite, HA, does not occur in biological systems. Biological apatites have been described as 'Ca-deficient', nonstoichiometric, 'impure', or carbonate-containing apatites [59, 142, 219, 224, 225, 293, 336, 424]. Biological apatites are discussed in Chapter 6. b. *Calcium-Deficient Apatites*: Calcium-deficient apatites (ADP) are apatites with nonstoichiometric Ca/P molar ratios (i.e., less than 1.67, the Ca/P molar ratio of pure Ca-OH-apatite, HA,  $\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$ ). Synthetic Ca-deficient apatites are obtained from aqueous systems either by precipitation or hydrolysis methods, 25–100 °C, initial pH of preparation lower than

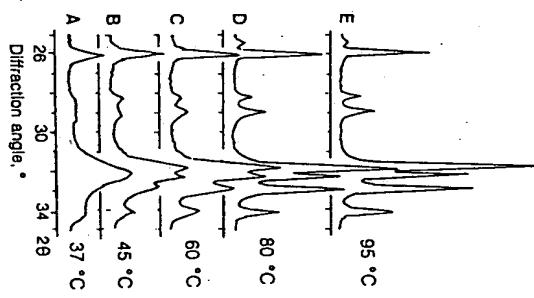
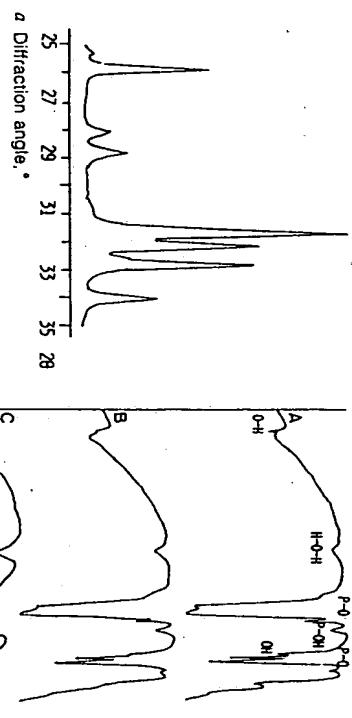


Fig. 2.11. Effect of temperature of precipitation on the 'crystallinity' of apatitic calcium phosphates. Apatite with the lowest crystallinity (reflected by broadest diffraction peaks) is obtained at 25 or 37 °C [224]. Crystallinity is also affected by the mode of preparation, e.g., apatite obtained from gel systems at 37 °C has crystallinity similar to C, more than A.



12 (fig. 2.11). The final pH is usually 5. The Ca/P molar ratios of such AP, even those prepared at 95–100 °C, can vary from 1.21 to 1.64. Besides a Ca/P molar ratio of less than the stoichiometric 1.67, the AP are characterized by the following properties: (a) larger  $\alpha$ -axis dimension compared to mineral OH-apatite or synthetic stoichiometric apatite obtained at temperatures above 800 °C; (b) presence of absorption bands due to the HPO<sub>4</sub><sup>2-</sup> groups in their IR absorption spectra (fig. 2.12b), and (c) formation of whillockite ( $\beta$ -TCP) with HA upon ignition or sintering above 700 °C, the  $\beta$ -TCP/HA ratio in the sintered product increasing with the decreasing Ca/P molar ratio of the unsintered AP [229].

*Example of a hydrolysis method of preparing AP:* 2 g CaHPO<sub>4</sub> (reagent grade) in 1 liter of calcium solution, Ca(Ac)<sub>2</sub>, 0.5 M, initial pH 5–7, stirring for 5 h at 95–100 °C.

*Example of a precipitation method of preparing AP:* Dropwise addition of calcium solution (250 ml Ca(Ac)<sub>2</sub>, 0.04 M) into a stirring phosphate solution (100 ml, 0.1 M (NH<sub>4</sub>)<sub>2</sub>HPO<sub>4</sub> + 650 ml dist. H<sub>2</sub>O) pH adjusted with HAc or NH<sub>4</sub>OH for initial pH ranging from 4 to 11, digested for at least 4 h at 95–100 °C. Precipitation may also be reversed (i.e., dropwise addition of phosphate solution into calcium solution), or by simultaneous dropwise addition of calcium and phosphate solution into a solution of NH<sub>4</sub>OH.

AP of varying Ca/P molar ratio (lower than 1.67) may also be prepared by the titration of saturated solution of Ca(OH)<sub>2</sub> with H<sub>2</sub>PO<sub>4</sub><sup>-</sup>; or by the hydrolysis of DCPD or of OCP in Ca-containing solutions at 60 to 100 °C, initial pH of solution 7. AP may also be obtained from gel systems, 37 °C, initial pH of the gel system, above 7.0.

A typical XRD pattern and IR spectra of AP are shown in figure 2.12a and b respectively. The  $\alpha$ -axis dimensions of AP are larger than that of pure HA (table 2.1) due to HPO<sub>4</sub><sup>2-</sup> incorporation [242, 247]. Ca/P molar ratio range from 1.3 to 1.61 (table 2.1); with typical acicular or needle-like morphology (fig. 2.12c).

*Biological occurrence:* Unsubstituted Ca-deficient apatites, AP does not occur in biological systems. As discussed in Chapter 6, biological apatites normally contain carbonate, sodium, and magnesium as minor constituents.

#### 8. Substituted Apatites

*a. Carbonate Apatites.* Synthetic CO<sub>3</sub> apatites have been classified as type A or type B depending on the mode of CO<sub>3</sub> substitution [46, 97, 293]: CO<sub>3</sub>-for-OH (type A), or CO<sub>3</sub>-for-PO<sub>4</sub> (type B).

Fig. 2.12. a XRD of apatitic calcium phosphate (Ca-deficient apatite) precipitated at 95 °C initial pH 7.5. b IR spectra of apatitic precipitates obtained at different temperatures (A) 45 °C; (B) 80 °C; (C) 100 °C. The loss of resolution in the IR spectra (e.g., A and B compared to C) reflects the decrease in crystallinity similar to that shown in XRD patterns (fig. 2.11). The presence of P-O-H absorption band (due to the presence of HPO<sub>4</sub><sup>2-</sup> groups) is a characteristic feature in the IR spectra of Ca-deficient apatites. c SEM of Ca-deficient apatite crystals with XRD patterns shown in figure 2.12a and IR spectrum in figure 2.12b(A).

b. *Infrared Spectroscopy*: IR spectra are caused by the different modes of vibrations and rotation of functional groups in a compound. The absorption band in the IR spectra originate when a molecule is raised from one molecular energy level to another of higher energy due to the absorption of radiation. The band positions,  $\nu$ , are expressed in reciprocal centimeters ( $\text{cm}^{-1}$ ) and are proportional to the force constant,  $f$ , between atoms or groups of atoms having reduced mass,  $\mu$ , which for two atoms may be calculated using the formulas below [183]:

$$\nu = \frac{1}{2\pi\mu} [f]^{1/2}$$

$$\mu = \frac{m_1m_2}{m_1 + m_2}$$

The factors determining the frequency of absorption are: bond elasticity (force constant,  $f$ ); relative masses of the bonded atoms. Others factors which may cause shifts in frequency of the absorption bands are electrical effects, steric effects, nature, size and charges of neighboring atoms, phase changes and hydrogen bonding.

In summary, the general principles which are useful in correlating the spectra with the molecular structure are: (a) each vibrational frequency or spectral band is related to a definite motion (e.g., stretching or bending) of the vibrating atoms; (b) each specific configuration of the atoms forming the radical will produce a characteristic vibrational spectrum; (c) the vibrational frequency is dependent both on the masses of the atoms and the internal forces which maintain the configuration of the molecule (such as interatomic distances), and (d) changes in the environment of the molecular groups will alter the equilibrium parameter of the molecular group (symmetry) and hence may cause the appearance of inactive vibrational modes and/or the removal or loss of degeneracies of others [147, 148, 183, 209].

In the case of synthetic and biological Ca-P, IR analyses give the following information: (a) identity; (b) purity, whether uni- or multiphasic; (c) presence of functional groups (e.g.,  $\text{HPO}_4^{2-}$ ,  $\text{CO}_3^{2-}$ ,  $\text{PO}_4^{3-}$ ,  $\text{PO}_7^{4-}$  organic component, etc.); (d) environment of the functional groups (whether in free state or in crystal field, whether surface or lattice-bound); (e) effect of the incorporation of one element on the vibration frequency of other functional groups (e.g., effect of the incorporation of  $\text{CO}_3^{2-}$  or  $\text{F}^-$  on the character and frequency of the vibration bands of the  $\text{PO}_4^{3-}$  or  $\text{OH}^-$ ) (fig. 2.8b); (f) type of substitution (e.g.,  $\text{CO}_3$ -for- $\text{OH}$  or  $\text{CO}_3$ -for- $\text{PO}_4$  in the apatite lattice) (table 2.3); (g) 'crystallinity', whether well crystallized, poorly crystallized or 'amorphous' as deduced from the resolution or loss of resolution of the vibration bands (fig. 2.12b); (h) type and relative amount of constituent, e.g.,  $\text{HPO}_4$  or  $\text{CO}_3$ - $\text{Mg}$  substitution in  $\beta$ -TCP.

Table 2.6. IR absorption bands for OCP and AP\* [148, 269]

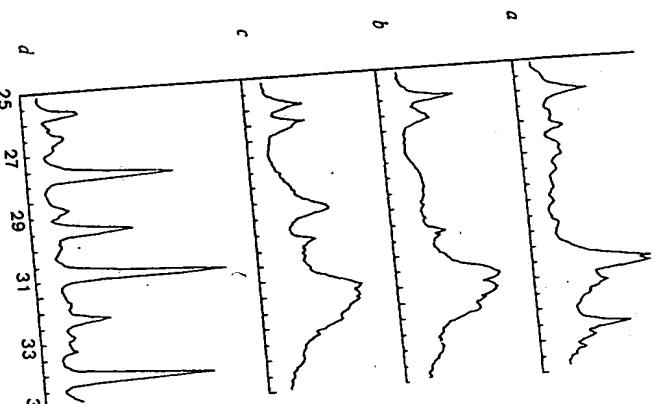
IR bands, $\text{cm}^{-1}$	Assignments
3,800-3,000	$\text{H}_2\text{O}$ of crystallization (OCP)
3,700-3,000	adsorbed $\text{H}_2\text{O}$ (AP)
3,580	$\text{O}-\text{H}$ , $(\text{OH})$ group
1,615	$\text{H}_2\text{O}-\text{H}$ , $\text{H}_2\text{O}$ of crystallization (OCP)
1,615	adsorbed $\text{H}_2\text{O}$ (AP)
1,454, 1,414	$\text{C}-\text{O}$ of $\text{CO}_3$ groups in $\text{CO}_3$ -AP
1,280, 1,200	$\text{P}-\text{OH}$ bending modes, $\text{HPO}_4$ groups
1,108, 1,194	$\text{P}-\text{O}$ and $\text{P}-\text{OH}$ , $\text{HPO}_4$ and $\text{PO}_4$ groups
1,119, 1,098 (F-AP)	
1,114 ( $\text{CO}_3$ -AP)	
1,078, 1,060(sh)	1,080(sh), 1,030
1,040, 1,024	$\text{F}-\text{O}$ in $\text{HPO}_4$ and $\text{PO}_4$ groups
964	
910, 869	965 (F-AP)
865 (AP)	$\text{P}-\text{O}$ or $\text{PO}_4$ group
873 ( $\text{CO}_3$ -AP)	$\text{C}-\text{O}$
630	$\text{O}-\text{H}$ of $\text{OH}$ group
628, 600, 561	620, 600, 564 (F-AP)
600, 563 ( $\text{CO}_3$ -AP)	$\text{P}-\text{O}$ or $\text{PO}_4$ groups
525	525
470, 450	$\text{HO}-\text{PO}_3$ bending mode in $\text{HPO}_4$
471	$\text{P}-\text{O}$ of $\text{PO}_4$ groups
344	344
368 (F-AP)	$\text{P}-\text{O}$ of $\text{PO}_4$ groups
365(sh) ( $\text{CO}_3$ -AP)	

\*Apatites obtained by hydrolysis of OCP in solutions containing  $\text{Ca}^{2+}$ ,  $\text{HPO}_4^{2-}$ ,  $\text{F}$ , or  $\text{CO}_3^{2-}$ .

The approximate band assignments for each of the ionic groups in OCP and in several synthetic AP are summarized in table 2.6 and the IR spectra of some Ca-P compounds are shown in figures 2.5b, 2.6b and 2.8b.

The differences in the crystal properties of the different types of Ca-P are reflected in their IR spectra (fig. 2.6). In the case of ACP of different composition, IR analyses give more information than XRD. While XRD give similar XRD patterns for several types of ACP (e.g., fig. 2.4a), the IR spectra can show the functional group (e.g., carbonate or pyrophosphate)

#### 4. Transformations of Calcium Phosphates *in vitro*



**OCP $\rightarrow$ AP transformation** in studies where only  $\text{Ca}^{2+}$  or only  $\text{Pi}$  ions are present in the hydrolyzing solutions with or without the presence of other ions (e.g.,  $\text{Mg}^{2+}$ ,  $\text{F}^-$ ,  $\text{CO}_3^{2-}$ , citrate ions, etc.) most probably proceeds by the process of dissolution and reprecipitation since the only source of  $\text{Pi}$  or  $\text{Ca}^{2+}$  ions necessary for the formation of AP would be the dissolving OCP crystals [270]. However, in cases (in vitro or in vivo) where the solution is saturated with  $\text{Ca}^{2+}$  and  $\text{Pi}$  [64, 129, 130], the OCP $\rightarrow$ AP transformation could proceed by in situ autocatalytic hydrolysis. In either case, the AP formed in the absence of critical concentrations of  $\text{F}^-$  or  $\text{CO}_3^{2-}$  in solution at near neutral pH are seen at about  $864 \text{ cm}^{-1}$ . The  $\text{HPO}_4^{2-}$ -bands in OCP are seen at 913, 868 and 527 [148], as summarized in table 2.5.

#### b. Thermally-Induced Transformations of OCP

TGA analyses of OCP show the different amounts of weight loss with temperature of ignition [7, 208]. IR spectra of ignited products show the transformation of OCP to  $\beta\text{-Ca}_2\text{P}_2\text{O}_7$ , after heating between 300 and 400 °C and to  $\beta\text{-Ca}_3(\text{PO}_4)_2$ , after heating above 700 °C, confirming results reported earlier by Fowler et al. [148]. XRD patterns before and after heating showed the stability of OCP structure even after heating at 100 °C, collapse of the structure after heating at 200 °C, and formation of other Ca-P phases at other temperatures (fig. 4.8). Attempts to compare the thermal stability of pure OCP with that of human enamel to demonstrate the possible presence of OCP in the latter were not successful [148].

#### 4.6. Tricalcium Phosphate, Whitlockite, $\text{Ca}_3(\text{PO}_4)_2$

##### a. Solution-Mediated Transformations

Pure whitlockite,  $\beta\text{-TCP}$ ,  $\text{Ca}_3(\text{PO}_4)_2$ , is not obtained from aqueous systems. It is obtained only from solid-state reactions at temperatures above 800 °C [219, 386]. However,  $\beta\text{-TCP}$  or  $\beta\text{-TCMP}$  are reported to transform to other types of Ca-P phases in solution. Pure  $\beta\text{-TCP}$  transforms to AP in distilled  $\text{H}_2\text{O}$  or in  $\beta\text{-TCP}\rightarrow\text{AP}$ . Pure  $\beta\text{-TCP}$  ceramic has also been shown to transform solutions at 100 °C.  $\beta\text{-TCP}$  ceramic has also been shown to transform to apatite in vivo [97, 264]. Mg-substituted  $\beta\text{-TCP}$ , i.e.,  $\text{Ca}^{2+}$ -containing solutions at 100 °C.  $\beta\text{-TCP}$  prepared from an aqueous system (with or without subsequent sintering at 950 °C), was not observed to transform to AP.  $\beta\text{-TCP}\rightarrow\text{OCP}$  transformation was observed in acidic solution (pH 5) at 60 °C [292].

#### 4. Transformations of Calcium Phosphates *in vitro*

The transformation of ACP, DCPD, DCP and OCP to apatite from solution containing either only  $\text{Ca}^{2+}$  or only  $\text{Pi}$  ions results in the formation of Ca-deficient apatites, with incorporation of  $\text{HPO}_4^{2-}$  from solutions similar to those obtained by precipitation at pH below 12. The incorporation of other ions present in the solution (e.g.,  $\text{Mg}^{2+}$ ,  $\text{Sr}^{2+}$ ,  $\text{CO}_3^{2-}$ ,  $\text{F}^-$ , etc.) in the forming 'AP' is due to dissolution and reprecipitation processes, i.e., dissolution of ACP, DCPD, DCP or OCP and reprecipitation of AP.

Transformation of OCP to Mg-substituted whitlockite,  $\beta\text{-TCMP}$ , has not been observed *in vitro*. This may be due to the stabilizing effect of Mg on OCP. However, although Mg is also known to stabilize DCPD, DCPD $\rightarrow$   $\beta\text{-TCMP}$  transformation in vitro is readily accomplished (see Chapter 4.3).

*b. Thermally-Induced Transformations* TGA analyses of Mg-substituted whitlockite,  $\beta$ -TCPMP, prepared either by hydrolysis or direct precipitation, was shown to contain  $\text{HPO}_4^{2-}$  as indicated by the formation of  $\text{Ca}_3\text{P}_2\text{O}_7$ , as one of the pyrolysis products [208]. The presence of  $\text{HPO}_4^{2-}$  in  $\beta$ -TCPMP is evident from its IR spectrum (fig. 2.9b). It is therefore likely that synthetic and biological  $\beta$ -TCPMP may be more appropriately characterized as  $(\text{Ca},\text{Mg})(\text{HPO}_4\text{PO}_4)_2$  rather than  $(\text{Ca},\text{Mg})(\text{PO}_4)_2$ .

$\beta$ -TCP is transformed to  $\alpha$ -TCP when sintered above 1300 °C.  $\text{CaCO}_3$  is transformed to  $\text{Ca}_3\text{P}_2\text{O}_7$  when sintered above 1300 °C.

#### 4.7. Apatitic Calcium Phosphates

##### a. Solution-Mediated Transformations

$\text{AP} \rightarrow \text{DCPD}$  transformation was demonstrated when a whole tooth was suspended in acidic phosphate solution at 25 and 37 °C, resulting in the formation of DCPD crystals on the enamel and dentin surfaces [232] depending on the initial pH of the phosphate solution (see Chapter 5). Formation of DCPD crystals on powdered human enamel treated with phosphoric acid has also been reported [77].  $\text{AP} \rightarrow \text{DCPD}$  partial transformation has also been observed inside a tooth and on human bones [258]. Seeded growth of DCPD [185] or OCP [362] on synthetic or biological AP is considered direct formation of Ca-P phases rather than transformation of one Ca-P phase to another. However, the possibility of partial dissolution of 'seed' Ca-P and precipitation of another Ca-P phase cannot be excluded.

##### b. Thermally-Induced Transformations

Pyrolysis of Ca-deficient or nonstoichiometric synthetic 'AP' results in the formation of  $\beta$ -TCP and/or HA, the  $\beta$ -TCP/HA ratio of the pyrolysis or ignited products reflecting the Ca/P of the AP before ignition [229, 369, 394]. Substitutions in the apatite contribute to its thermal stability, or instability. The type and amount of substitution determines the substituents in the  $\beta$ -TCP or HA phases of the ignited material and also determines the  $\beta$ -TCP/HA ratio in the ignited product. For example, substitutions of about 6 wt% CO<sub>3</sub> results in the formation of only HA in the ignited product, below this amount,  $\beta$ -TCP forms with HA, above, CaO forms with HA [242]. The substitution of F promotes the formation of mainly HA in the ignited product, while the presence of Mg or Sr promotes the formation of a greater amount of Mg-substituted or Sr-substituted  $\beta$ -TCP with HA. Since the

formation of  $\beta$ -TCP upon ignition of synthetic apatites prepared from aqueous systems is related to the presence of  $\text{HPO}_4^{2-}$  in the apatite before ignition, it is apparent that some substituents (e.g., Mg, Sr) allow the simultaneous incorporation of  $\text{HPO}_4^{2-}$  while other substituents (e.g., F or CO<sub>3</sub>) do not [227, 265, 272].

#### 4.8. Transformations of Other Calcium Compounds

Other calcium compounds have been reported present in the oral environment. These compounds include calcite,  $\text{CaCO}_3$ , and fluorite,  $\text{CaF}_2$ .  $\text{CaCO}_3 \rightarrow \text{AP}$  transformation can take place during the hydrolysis of  $\text{CaCO}_3$  in solutions containing  $\text{PO}_4^{2-}$  and/or  $\text{CO}_3^{2-}$  or  $\text{F}^-$  [253]. This transformation is suppressed by the presence of Mg<sup>2+</sup> whether present in  $\text{CaCO}_3$  (e.g.,  $(\text{Ca},\text{Mg})(\text{CO}_3)_2$ , dolomite) or present in the hydrolyzing solution [252].  $\text{CaCO}_3 \rightarrow \text{DCPD}$  transformation has also been observed [258].  $\text{CaF}_2 \rightarrow \text{AP}$  or FHA or FA transformation can take place in the presence of Ca<sup>2+</sup> and PO<sub>4</sub><sup>2-</sup> ions [253] as discussed in Chapter 7. Transformation of CaF<sub>2</sub> to AP was also observed when DCPD was simultaneously present [397]. This transformation is of biological relevance in dental caries management by F treatments [347] and is discussed in Chapter 7.

#### 4.9. Summary

Solution-mediated transformation of one type of Ca-P to another (fig. 4.1) can proceed by the processes of partial or complete dissolution and reprecipitation, many ions becoming incorporated in the transformation product. Some transformations may also proceed *in situ*, pH, temperature, and composition of the media may either promote or suppress the transformation reactions.

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of  $\beta$ -TCP above 700 °C [157, 220], the formation of  $\beta$ -TCP being related to the pyrophosphate and presence of  $\text{HPO}_4$  in the original apatite [219, 220, 243, 394, 420]. Ca-deficient apatites are also known to form  $\beta$ -TCP upon ignition [219, 229, 243, 394, 420]. Ignition of type B apatites at temperatures between 300 and 400 °C causes a contraction in the  $a$ -axis attributed to the  $\text{HPO}_4$ -for- $\text{PO}_4$  substitution in the unignited apatite [190, 220, 247]. Earlier

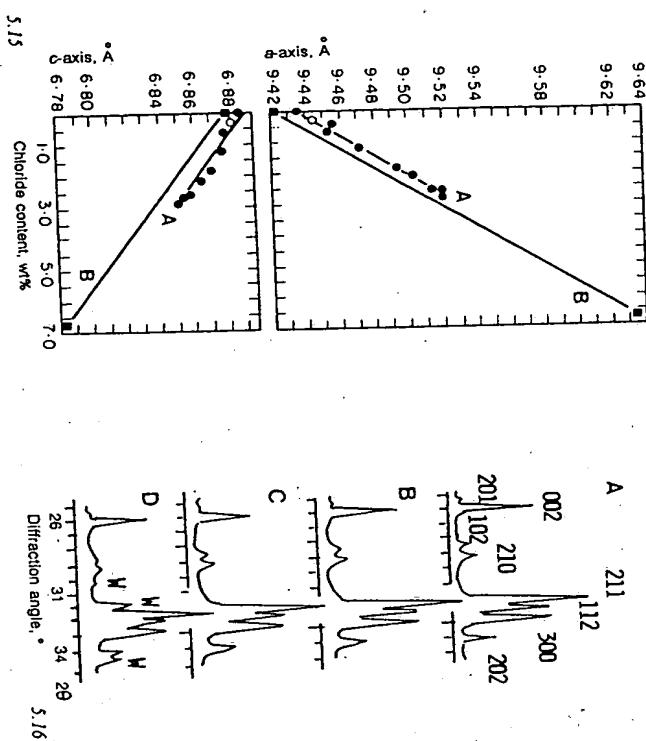


Fig. 5.15. Effect of Cl incorporation on the lattice parameters of type A (from

nonaqueous systems, 1,000 °C) and type B (from aqueous, 95–100 °C) apatites, A and B, respectively. Type A apatites allow the complete substitution of Cl-for-OH while type B apatites allow limited substitution in spite of the abundance of  $\text{Cl}^-$  ions in the solution [220].

Fig. 5.16. Mg substitution in synthetic apatites prepared by precipitation at 95–100 °C from solutions with  $\text{Mg}/\text{Ca}$  molar ratios: (A) 0/100; 2/98; (C) 3/97; (D) 5/95. The corresponding Mg contents in apatites (A–C) are: 0.03 (A), 0.14 (B), and 0.27 wt% Mg (C). Mg-substituted whillockite phase (W) forms (D) the solution.  $\text{Mg}/\text{Ca}$  molar ratio exceeds 3/97 or 0.031 [227].

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reports suggested that Ca-deficient apatites are more soluble than stoichiometric apatite [338]. However, no systematic studies on the dissolution properties of apatites containing different levels of  $\text{HPO}_4$ -for- $\text{PO}_4$  substitute have been made.

#### 5.6. Effect of Magnesium

The incorporation of Mg in synthetic apatites is very limited (maximum of about 0.4 wt% Mg) unless carbonate or fluoride ions are simultaneously incorporated with Mg [227]. The amount of Mg incorporated in the apatite is proportional to the Mg concentration in the solution. However, when the solution  $\text{Mg}/\text{Ca}$  molar ratio is higher than 0.31, Mg-substituted whillockite,  $\beta$ -TCMP, forms, the  $\beta$ -TCMP/AP ratio in the precipitate increasing with increasing  $\text{Mg}/\text{Ca}$  in the solution (fig. 5.16). The incorporation of Mg is

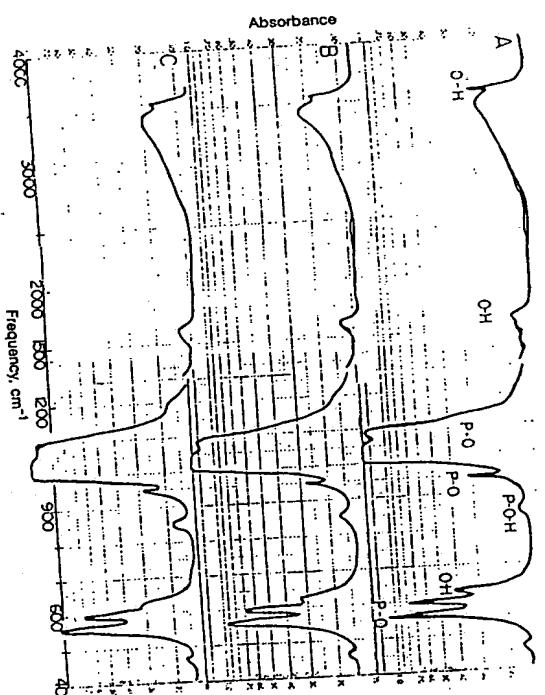


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Fig. 5.17. IR spectra of Mg-containing apatites showing loss of resolution of the  $\text{PO}_4$  absorption bands with increasing Mg in the apatite. Mg content same as in fig. 5.18.

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Mg-containing AP (fig. 5.18), and (d) increase in extent of dissolution. These effects are summarized in table 5.1.

increased by the simultaneous incorporation of F or CO<sub>2</sub>. The limited incorporation of Mg is also observed in apatites prepared at high temperature (above 900 °C) by solid-state reaction [387].

The presence of Mg in the apatite causes the following effects on its properties [227], 268]: (a) decrease in  $\alpha$ -axis dimension; (b) decrease in crystallinity as shown in XRD patterns and IR spectra (fig. 5.17); (c) increase in HPO<sub>4</sub> incorporation as shown by the higher  $\beta$ -TCP/HA ratio is sintered

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in the apatite causes the following effects on its properties [227], 268]: (a) decrease in  $\alpha$ -axis dimension; (b) decrease in crystallinity as shown in XRD patterns and IR spectra (fig. 5.17); (c) increase in HPO<sub>4</sub> incorporation as shown by the higher  $\beta$ -TCP/HA ratio is sintered

### 5.7. Effect of Strontium

Sr is easily incorporated into either type A (from nonaqueous systems) [181] or type B (from aqueous systems) [80, 219, 249] apatites, the Sr-for-Ca substitution resulting in the expansion of the  $\alpha$ - and  $c$ -axis dimension due to the larger ionic radius of Sr (table 5.1; fig. 5.19). In type B apatites, Sr incorporation is greater at basic (pH 9) than acidic (pH 5) pH conditions (fig. 5.20).

Sr substitution in the apatite showed no significant difference in crystallinity but showed some loss of resolution in the absorption bands of the PO<sub>4</sub> groups in the IR spectra (fig. 5.21). In addition, in the IR spectra, Sr-substituted OH-apatites disturbed the O-H bending mode as shown by the absence of the O-H absorption bands at 633 cm<sup>-1</sup>, despite its known presence, Sr-substituted apatite was shown to be more soluble than Sr-free apatite [231, 272, 363], as shown in figure 5.22.

### 5.8. Effect of Other Cations

Like Sr, divalent ions barium, Ba, and lead, Pb, can substitute for Ca in type A and type B apatites, forming Sr<sub>10</sub>(PO<sub>4</sub>)<sub>6</sub>(OH)<sub>2</sub>, Ba<sub>10</sub>(PO<sub>4</sub>)<sub>6</sub>(OH)<sub>2</sub> and Pb<sub>10</sub>(PO<sub>4</sub>)<sub>6</sub>(OH)<sub>2</sub> as end members of the isomorphous series. These ions being larger than Ca<sup>2+</sup>, cause expansion in both the  $\alpha$ - and  $c$ -axis dimensions when they substitute in the apatite lattice (table 5.1). Their incorporation also causes changes in the IR absorption spectra, notably the PO<sub>4</sub> absorption bands and the masking of the O-H bands (l vibrational vibration mode), as shown in figure 5.23. The detailed effects of Ba or Pb incorporation on the dissolution properties of apatites have yet to be studied.

Other polyvalent ions, e.g., aluminum, Al<sup>3+</sup>, manganese, Mn<sup>2+</sup>, zinc, Zn<sup>2+</sup>,

were shown to cause a decrease in the crystallinity of the apatites (fig. 5.24, 5.25). Systematic studies on the possible substitutions of these cations in the apatite and their effect on solubility have not been reported.

Monovalent ions, e.g., sodium, Na<sup>+</sup>, potassium, K<sup>+</sup>, lithium, Li<sup>+</sup>, can be incorporated in synthetic apatites. The Na<sup>+</sup>, being similar in size to Ca<sup>2+</sup>, is not expected to cause any effect on lattice parameters; K<sup>+</sup> being larger than

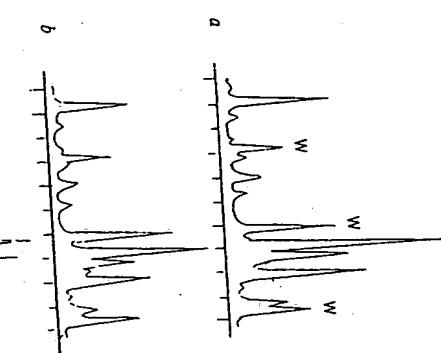


Fig. 5.18. Effect of Mg incorporation in the apatite on the formation of β-TCP (Mg-substituted) after ignition. XRD of apatites ignited at 800 °C: (a) Mg in apatite, 0.05 wt%, β-TCP/HA ratio = 33/67; (b) Mg in apatite, 0.14 wt%, β-TCP/HA ratio = 46/54; (c) Mg in apatite, 0.27 wt%, β-TCP/HA ratio = 51/49. W on the x-ray diffraction patterns (A) indicate the major peaks of the whitlockite or β-TCP phase.